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Title: **NEW INTERPHASE IN TWO-PHASE FLUIDIZED BEDS**

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A new interphase force in two-phase fluidized beds

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Abstract

Mesoscale structures such as particle clusters have been observed both in experiments and in numerical simulations of circulating fluidized beds. In a numerical simulation, in order to account for the effects of such mesoscale structures, the computational grids have to be fine enough. The use of such fine grids is impractical in engineering applications due to excessive computational costs. To predict the macroscopic behavior of a fluidized bed with reasonable computation cost, we perform a second average over the averaged equations for two-phase flows. A mesoscale inter-phase exchange force is found to be the correlation of the particle volume fraction and the pressure gradient. This force is related to the mesoscale added mass of the two-phase flow. Typically, added mass for particle scale interactions is negligible in gas-solid flows since the gas density is small compared to density of solid particles. However, for a mesoscale structure, such as a bubble, the surrounding media is the mixture of gas and particles. The "surrounding fluid" density experienced by the the mesoscale structure is the density of the surrounding mixture. Therefore the added mass of a mesoscale structure, such as bubbles, cannot be neglected.

The property of this new force is studied based on our numerical simulation of a fluidized bed using high grid resolution. It is shown that this force is important in the region where the particle volume fraction is high. The effects of the inhomogeneity to the interphase drag are also studied.

1 Introduction

It is now well-recognized fact that mesoscale structures, such as, bubbles, particle clusters and streamers exist in many circulating fluidized bed. Mesoscale interactions have important effects on the macroscopic behavior of an industrial sized fluidized bed. Usually, the size of mesoscale structure is smaller than the grid cell-size that is affordable to use in a numerical calculation. To account for effects of the mesoscale structures, we need to study their behavior and to develop a model for practical numerical calculations.

In this paper we shall demonstrate that these mesoscale structures are the direct consequence of inherent instabilities described in the averaged two-phase flow equations; and are not caused by the particle-scale interactions described by traditional kinetic theories. Particle-scale interactions do, however, modify the details of mesoscale structures. This is similar to high Reynolds number turbulence. Although the molecular viscosity controls the detailed energy dissipation mechanism at the Kolmogorov scale, the energy cascade is dominated by motion of large-scale eddies. Indeed, recently, Agrawal *et al.* (2000) performed two-dimensional simulations using a set of two-phase flow equations and kinetic theory to model effects of particle-particle interactions. They found that Reynolds stresses in the particle phase result mainly from the mesoscale interactions and the contribution from the kinetic theory of granular materials is negligible.

Using the ensemble phase averaging method (Zhang and VanderHeyden, 2000b), we derived a set of macroscopic equations. A new macroscopic force is found to describe the mesoscale interactions of the two phases. With the numerical simulation results we studied the properties of the new force term.

2 Numerical simulations without using a kinetic theory

To consider particle-particle interactions in a fluidized bed, it is customary now to use a kinetic theory. One of the fundamental assumptions of a kinetic theory requires the instantaneous binary collisions. This implies that particles do not interact with each other except in a collision. This assumption excludes the effects of particle-fluid-particle interactions, because this type of interaction is neither instantaneous, nor likely binary. A technique (Zhang and Rauenzahn, 1997, 2000) to study prolonged particle interactions and multiparticle interactions has been developed to study dense (nearly dense packing) granular systems. This technique, however, has not been applied to relatively dilute fluidized beds. As, mentioned above, the mesoscale interactions are dominated by the instability of the averaged two-phase flow equations at the mesoscale level, not at the particle scale. This scale separation enables us to approximate mesoscale structures without explicitly considering particle-scale interactions, even though the particle-scale interactions modify the details of mesoscale interactions. From this point of view, in our numerical simulation, we employ only the simplest set of averaged two-phase flow equations.

$$\frac{\partial}{\partial t}(\theta_c\rho_c\mathbf{u}_c) + \nabla\cdot(\theta_c\rho_c\mathbf{u}_c\mathbf{u}_c) = -\theta_c\nabla p - \theta_d\mathbf{f} + \theta_c\rho_c\mathbf{g}, \tag{1}$$

$$\frac{\partial}{\partial t}(\theta_d\rho_d\mathbf{u}_d) + \nabla\cdot(\theta_d\rho_d\mathbf{u}_d\mathbf{u}_d) = -\theta_d\nabla p + \theta_d\mathbf{f} + \theta_d\rho_d\mathbf{g}, \tag{2}$$

where $\mathbf{f}_d$ is the particle drag

$$\mathbf{f}_d = -\frac{3}{4d}\theta_c C_d \rho_g |\mathbf{u}_d - \mathbf{u}_c|(\mathbf{u}_d - \mathbf{u}_c)\,. \tag{3}$$

The symbols $\mathbf{u}$, p, ρ, $\mathbf{g}$ and θ stand for velocity, pressure, density and volume fraction respectively. The subscripts d and c stand for the disperse and continuous phases respectively.

The drag coefficient C_d, due to White (1974), is calculated as

$$C_d = C_\infty + \frac{24}{Re} + \frac{6}{1+\sqrt{Re}}, \quad Re = \frac{|\mathbf{u}_d - \mathbf{u}_c|d}{\nu_c}, \quad C_\infty \approx 0.4. \tag{4}$$

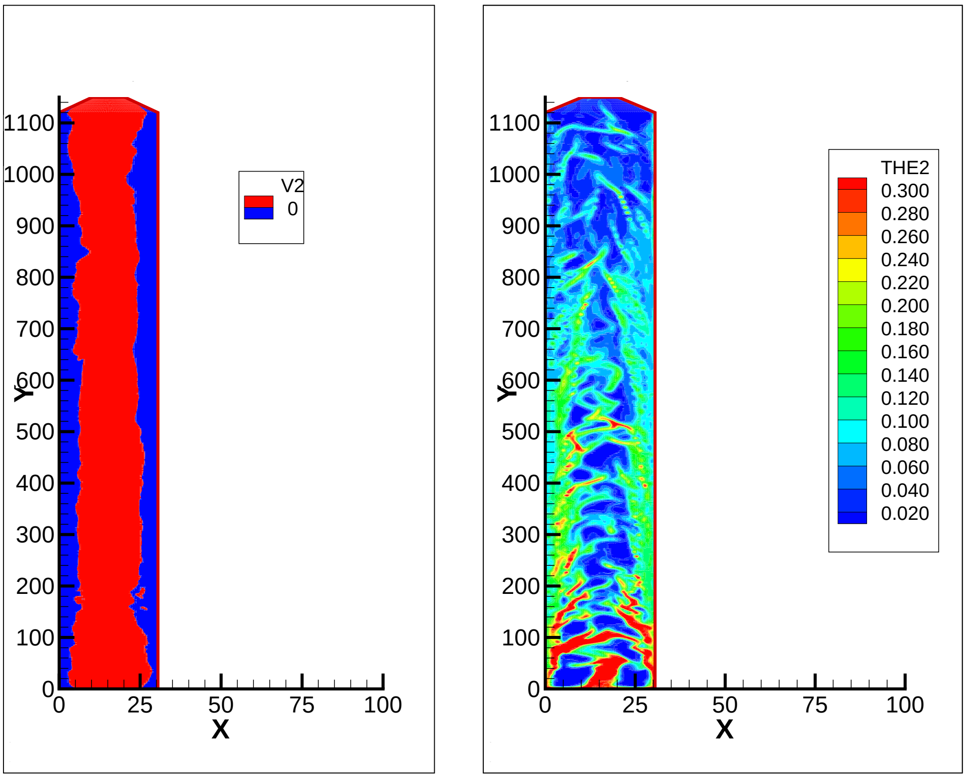

Figure 1: A snapshot of solid phase velocity contour and particle volume fraction contour on a two dimensional simulation. The particle size is $76\mu m$ in the bed simulated. Gas velocity at the bottom is 3.7 m/s and the solid flux is 98 $kg/m^2/s$.

where ν_c is the kinematic viscosity of the continuous phase.

We performed simulations with this set of averaged equations of the fluidized bed studied by Bader *et al.* (1988). Figure 1 shows one of the snap shots of velocity and particle volume fraction contours. It shows clearly the core-annular flow pattern. The presence of mesoscale structures is evident.

We also used the set of averaged equations to perform three-dimensional simulation (Zhang and VanderHeyden 2000) and compared our numerical results to the experiment performed by Van den Moortel *et al.* (1998). At high enough grid resolution, mesoscale structures are observed as shown in Figure 2. This figure shows the contour of the solid volume fraction on mid-plane of the square duct. In this geometry, particles concentrated in the four corners of the square duct instead of the wall of the duct, therefore the core annular flow pattern is not shown as clearly as in Figure 1. Good quantitative agreement between numerical results and experiment were found in this simulation. For instance, the calculated mass fluxes are compared to experimental values in Figure 3. This agreement with data is further evidence that the macroscopic behavior of a gas-solid fluidized bed is dominated by mesoscale interactions.

Although, these mesoscale scale structures can be captured with the fine grid resolution used in our simulation, direct application of the equations used to engineering practice is not realistic. To simulate 21 seconds of real time in the small

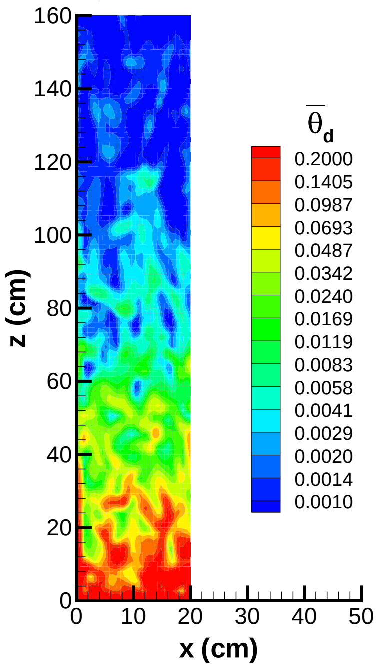

Figure 2: A snapshot of particle volume fraction contour on a mid-plane of the experimental device used by Van den Moortel *et al.*(1998). The experimental section of the device is a square duct with $20cm$ side, and $200cm$ in height. The overall volume fraction in the device is 3%. The particle material density is 2.4 g/cm^3, and mean diameter is $120\mu m$ with $20\mu m$ of standard deviation. The fluid is gas at room temperature.

fluidized bed of Van den Moortel *et al.*, we used an SGI Origin 200 machine with two processors in parallel. It took us 51 days of wall-clock time or about 100 CPU days. For engineering applications, we seek to derive a set of macroscopic equations that accounts for the effects of mesoscale interactions through models that can be used in a much less costly calculation.

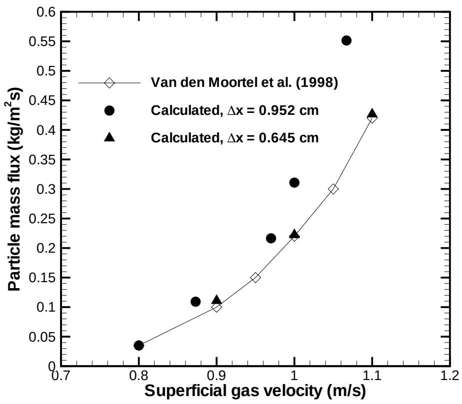

Figure 3: Comparison of calculated mass fluxes with the experimental values.

3 A new phase interaction forces at mesoscale

By performing an ensemble phase average of momentum equations we found a new exchange force $\mathbf{f}_m$ representing the mesoscale interactions (Zhang and VanderHeyden (2001b).

$$\theta_d \mathbf{f}_m = \overline{\theta_d' \nabla \cdot \boldsymbol{\sigma}_c'}, \tag{5}$$

where $\boldsymbol{\sigma}_c$ is the stress of the continuous phase averaged on the particle scale level. The primes denote the fluctuation of the quantity. The force $\mathbf{f}_m$ results from the correlation of fluctuations in volume fraction and fluctuations in stress divergence. It vanishes in a homogeneous flow. To understand the physical meaning of this force, let us consider a particle cluster with a constant volume fraction fluctuation θ_d'. Let V be the volume of the cluster. Then the integral

$$\int \theta_d' \nabla \cdot \boldsymbol{\sigma}_c' dV = \theta_d' \int_{\partial V} \boldsymbol{\sigma}_c' dS, \tag{6}$$

represents the interfacial force on the cluster surface. This force represents the interaction of the cluster and the surrounding medium. In the case of non-constant θ_d', the force $\mathbf{f}_m$ can be viewed as the averaged interfacial force acting on the fuzzy surface of clusters. Interactions between the mesoscale structures and the surrounding medium can be divided into a drag and an added mass force similar to the case for a particle in a fluid. Typically, in a gas-solid flow, gas inertia is negligible. For the case of mesoscale structures, the surrounding medium is not pure gas but a mixture of solid and gas, which has a much larger density than the gas. Therefore the mesoscale added-mass force between the two phases is important. In Figure 4, based on our high resolution simulation (Zhang and VanderHeyden, 2001a), the force $\mathbf{f}_m$ is shown as a function of height in the fluidized bed.

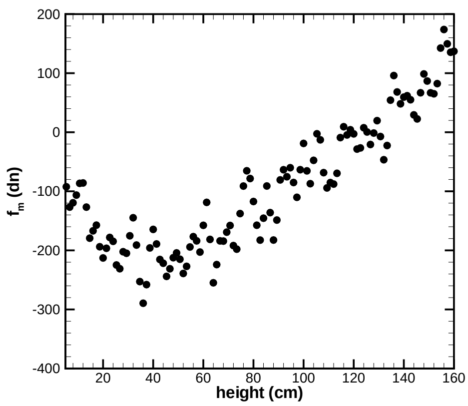

Figure 4: Mesoscale force $\mathbf{f}_m$ as a function of height. The superficial gas velocity is $1.1m/s$.

In the figure, the mesoscale force $\mathbf{f}_m$ is negative, resisting upward motion of the particle phase, in the lower half of the fluidized bed. It is positive, pushing the particle phase upward, in the upper half of the fluidized bed. In a statistically steady fluidized bed, solid volume fraction decreases with the height. Based on mass conservation, the particle phase accelerates vertically while the gas phase decelerates. At

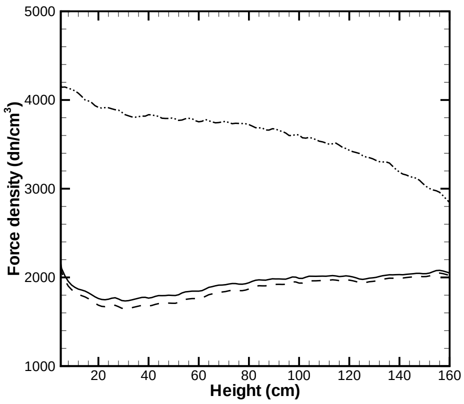

Figure 5: Averaged particle drag force as a function of height. The solid line is results from numerical simulation and the dashed line is calculated using the averaged gas velocity experienced by particles v defined in eq. (9). The dot and dash line is calculated using averaged relative velocity $\mathbf{u}_d - \mathbf{u}_c$. The superficial gas velocity is $1.1m/s$.

particle scale, the added mass effect resulting from such relative motion is negligible since gas density is small compared to the particle phase density. At the mesoscale level, however, the mesoscale structures, such as bubbles, move in a mixture of particles and gas. The effective density experienced by the mesoscale structure is of the order of the density of the mixture that is substantially large than the gas density. Therefore, mesoscale added mass is important while the particle scale added mass is negligible. The positive part of the force is due to the average cluster drag as a result of relative motion between the particle clusters and surrounding medium. The negative part of the force cannot be explained by the drag alone. It can only be explained by an added mass force since at the lower portion of the fluidized bed the relative acceleration between the two phases is large compared to that in the upper half.

The effect of the mesoscale is not only restricted to the mesoscale force. Within a particle cluster the particle phase falls in the wake generated by the leading part of the cluster and the relative velocity is significantly less than the averaged the relative velocity. Therefore the drag, $\mathbf{f}_d$, is significantly reduced as shown in Figure 3. If we used the averaged relative velocity experienced by the particles to calculate the drag force, close agreement with the numerical results are found as shown in Figure 5.

Both the mesoscale added mass and the reduction of drag contribute significantly to the macroscopic behavior of a fluidized bed. For the mesoscale added mass force we propose

$$\theta_d \mathbf{f}_m = -C_a \rho_m \left(\frac{\partial \mathbf{u}_d}{\partial t} + \mathbf{u}_d \cdot \nabla \mathbf{u}_d - \frac{\partial \mathbf{u}_c}{\partial t} - \mathbf{u}_c \cdot \nabla \mathbf{u}_c \right). \qquad (7)$$

where $\rho_m = \theta_d \rho_d + \theta_c \rho_c$ is the density of the mixture, and C_a is an added mass coefficient. The added mass coefficient is apparently dependent on the shape and the flow

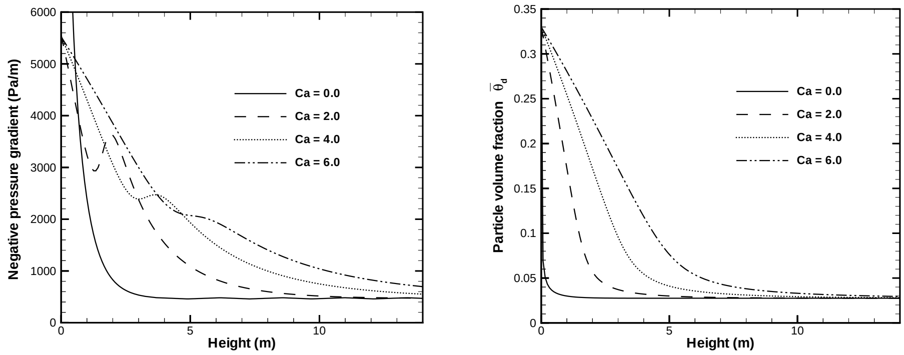

Figure 6: Vertical distribution of pressure gradient and averaged particle volume fraction calculated using different added mass coefficients C_a. The relative velocity reduction coefficient C_r is fixed at 0.9 in all the calculations.

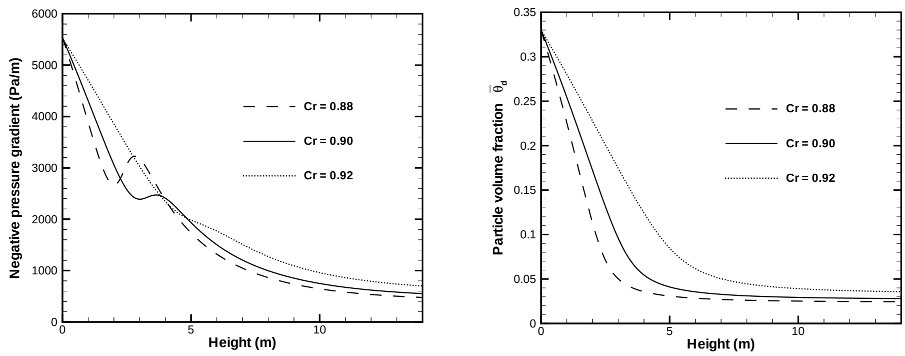

Figure 7: Vertical distribution of pressure gradient and averaged particle volume fraction calculated using different relative velocity reduction coefficient C_r. The added mass coefficient C_a is fixed at 4.0 in all the calculations

condition of the mesoscale structures. Ideally, in (7), the density ρ_m should be an averaged density outside a mesoscale structure rather than the mixture density. To avoid introduction of additional constitutive relation, we choose to use the mixture density until further study into the properties of mesoscale structure is conducted.

For the drag term, we propose (White, 1974)

$$\mathbf{f}_d = -\frac{3}{4d}\theta_c C_d \rho_g |v| v, \tag{8}$$

where v is the relative velocity in the vertical direction.

$$v = (1 - C_r)(u_{dz} - u_{cz}), \tag{9}$$

and C_r is relative velocity reduction coefficient.

Figures 6 and 7 illustrate the effects of the added mass coefficient C_a and coefficient of relative velocity reduction C_r in a one-dimensional vertical fluidized bed simulation. Note that these forces modifications significantly affect the pressure gradient and volume fraction profiles.

Conclusions

Averaged macroscopic equations for two-phase flows, considering effects of mesoscale structures, are derived. It is found that the mesoscale added mass is important to the macroscopic averaged equations since mesoscale structures are immersed in a mixture of gas and particles. The effective density in the mesoscale added mass is of the order of mixture density, not the gas density.

The presence of mesoscale structures reduces the relative velocity experienced by particles and the drag between the two phases. Our numerical results suggest that only when both the mesoscale added mass and the drag reduction are accounted for, the distribution of particle volume fraction along the height of a circulating fluidized bed can be predicted correctly.

Acknowledgments

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